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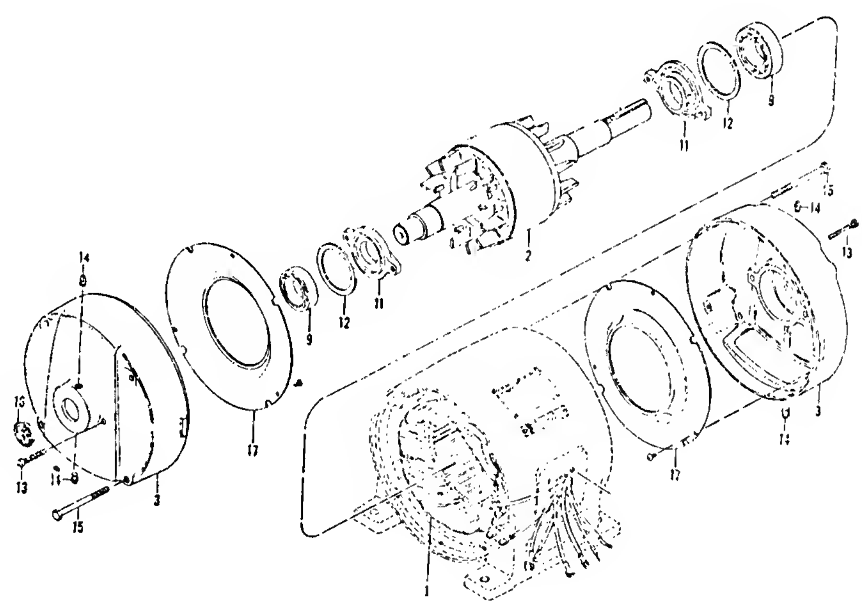
ECL 222

MEASURING MOTOR TORQUE-SPEED CURVES (A)

To a motor manufacturer exact information about the Torque-Speed characteristics of his motor means money. The more exactly he can measure it under all conditions, the more exactly he can design his product. Bill Tyler, Chief Engineer of the Rotating Electrical Machinery Department of Tamper Ltd., wanted more information. To get it he undertook the development of an instrument which would measure the transient torque-speed characteristics of his line of motors.



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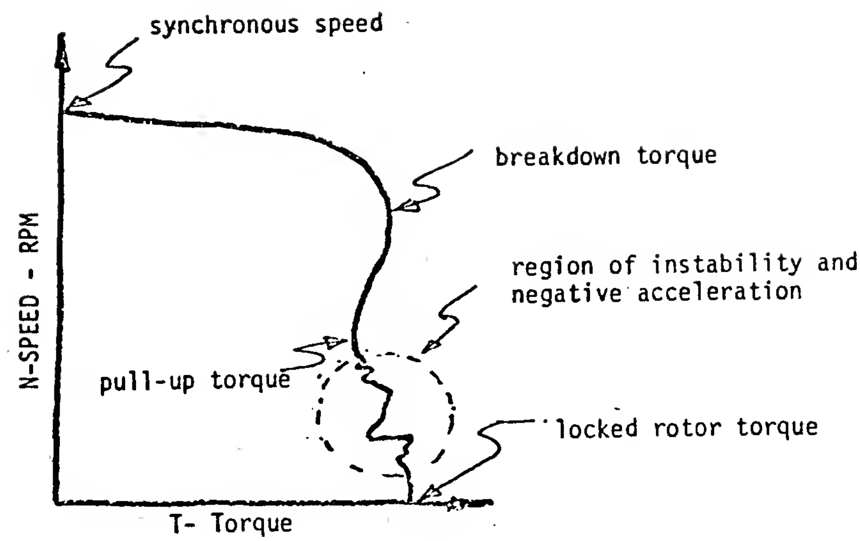


Fig. 1: T-N CURVE FOR INDUCTION MOTOR

horsepower is delivered at rated speed which is something less than synchronous speed. Industry standards define minimum values for required breakdown torque, locked rotor torque and pull up torque.

The motor design is based upon the torque requirements at rated speed and horsepower. Theory can be used to determine pull up torque to within 10% and breakdown torque to 20%. The errors are mainly due to the reactances which present theory cannot predict.

To evaluate a finished motor a dynamometer is used to measure the T-N curve. The determination of the complete T-N curve is very tedious. The standard check points, such as locked rotor torque etc., can be found quickly and accurately. But exact values are very difficult to obtain in the region of negative acceleration. Things change too quickly. Once Tamper tried to use 12 technicians to make accurate measurements in this region, but they still couldn't reduce the error to less than 20%.

An important feature of the Torque-Speed characteristic which cannot be predicted from theory nor easily measured on a dynamometer is the cusps or discontinuities in the curve (Fig. 2). Theory only predicts a smooth curve because it

MEASURING MOTOR TORQUE-SPEED CURVES (A)

Tamper Ltd., the electrical division of Canron Ltd., was founded in Montreal, Quebec, in 1934 as Electric Tamper and Equipment Co. of Canada Ltd. During World War II it became a major supplier of electric motors to the Canadian Navy. Since then it has continued to grow so that now it is the second largest motor manufacturer in Canada. The Montreal plant, employing 800 people, is responsible for the design and manufacture of a full line of integral horsepower motors from 1 HP to 5300 HP.

Bill Tyler is the chief engineer of the Rotating Electrical Machinery Department. He graduated in electrical engineering from McGill University in 1948. After graduation he worked for Tamper for six years on the mechanical design of electric motors. He left Tamper to work for several different companies. He has experience in the development of gyroscopes, aircraft navigation equipment, gunfire control systems, diesel simulators, and combustion systems. He considers the three years spent doing marketing studies a most important part of his career. To him, marketing is essential to the training of any engineer.

Tyler returned to Tamper to become corporate manager of Research and Development. Tamper has diversified interests, and the work carried out by his division was also diversified. Tyler supervised development projects ranging from hydraulic rock drills to railway alignment equipment.

Eventually the company found it was too diversified to operate efficiently with Central Research and Development. To shorten response time, each department was made responsible for its own research. As a result of reorganization Tyler became chief engineer of the Rotating Electrical Machinery branch, with a staff of 25.

Indeed it was on Tyler's recommendation that the Central Research and Development Division of the company was split. Tyler had concluded that a central research division was just something which Tamper could not afford. "Unless you are as big as Bell Telephone or General Electric, your research must be heavily guided by marketing."

One problem constantly confronting the designers of induction motors is the need for accurate Torque-Speed Curves.

The performance characteristic of an induction motor is summarized by its Torque-Speed (T-N) curve (Fig. 1). The rated

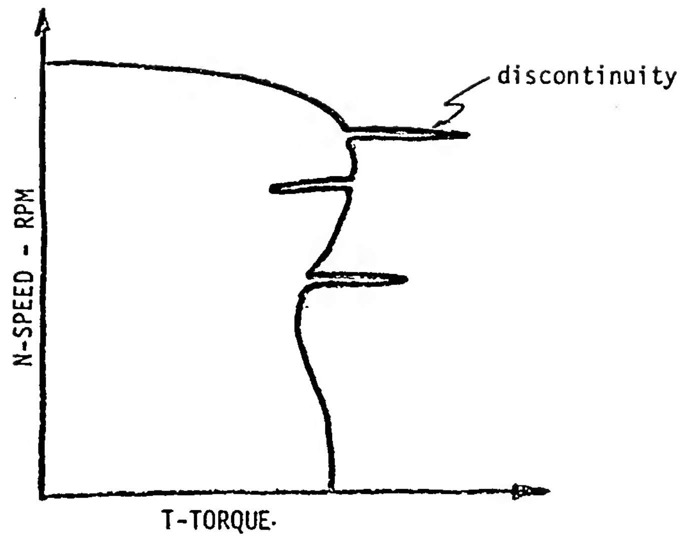


Fig. 2: DISCONTINUITIES IN T-N CURVES

assumes that the magnetic flux in the airgap between the stator and the rotor is sinusoidally distributed. The actual flux distribution is more complex and includes many harmonics. Normally the amplitudes of the harmonics are only 1/100 of the fundamental, and can be disregarded. Under some conditions, such as non-uniform airgap geometry or certain stator slot and rotor bar combinations, the amplitude of specific harmonics is magnified and affects the motor performance. The effect is often visualized as the fundamental sine wave and the prevalent harmonic driving two motors, each with its own performance characteristic but connected to the same shaft. The result is a dip or discontinuity in the T-N curve (Fig. 3). Usually if the n^{th} harmonic is prevalent the cusp will occur at $\frac{\text{synchronous speed}}{n}$.

Other irregularities which theory doesn't predict have also been noted in the T-N curve. Irregular locked rotor torque has been observed, the torque changing as a function of the rotor position. Tyler had seen some designs that change locked rotor torque by 50-60% if the rotor occurs at other speeds, and is referred to as Sub-Synchronous Crawling, the effect being less than with cogging torque (Fig. 4).

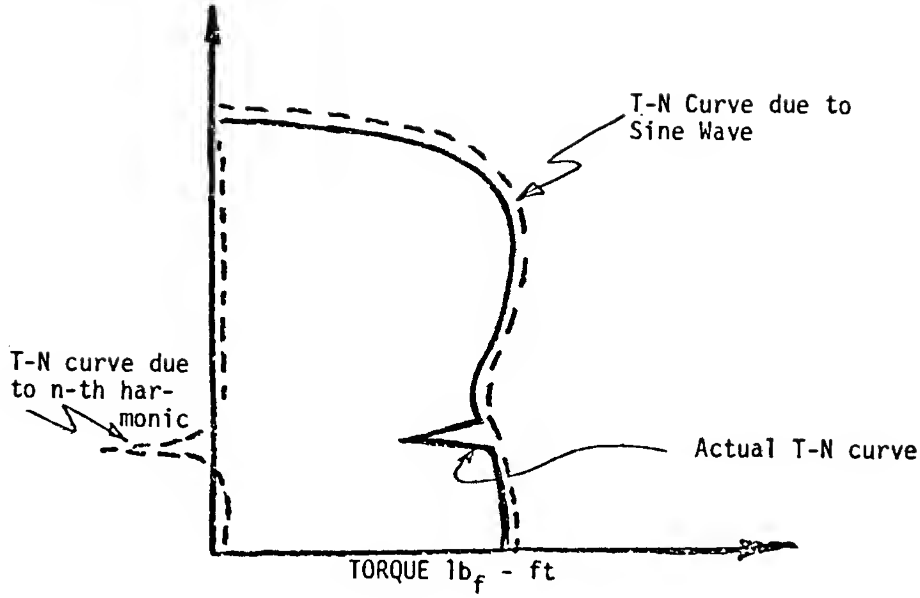


Fig. 3: EFFECT ON N-TH HARMONIC

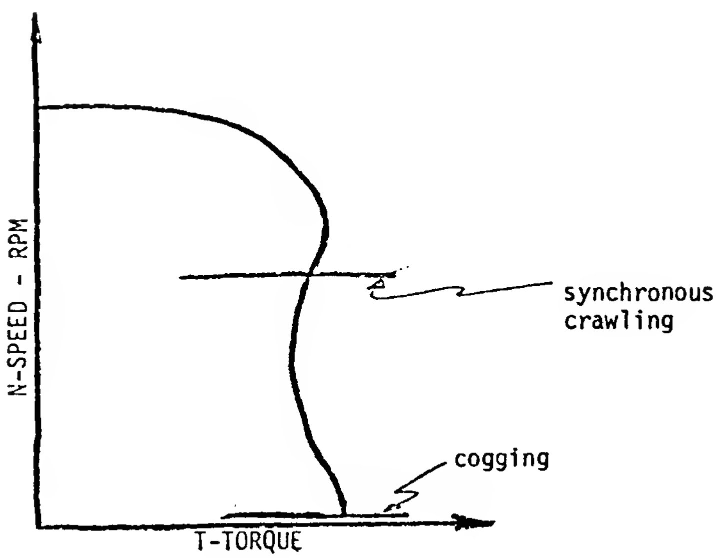


Fig. 4: VARYING TORQUES AT ONE SPEED

The difficulties of measuring T-N curves are reflected in the requirements set forth by NEMA (National Electric Manufacturers Association). The T-N performance must be within 25% of those specified and the manufacturer is liable when this range is exceeded. Theory and dynamometer testing are essential for the designer to maintain the performance in the required range.

Undetected discontinuities lead to nasty problems. For example, with a motor and load matched for performance, if the motor has an unforeseen discontinuity as the system accelerates, it can hang up at the discontinuity and burn out the motor.

To insure that their motors will meet specifications, Tamper's designers are forced to overdesign. They always design so that the expected T-N curve will exceed the requirements. They insure that the 25% deviation is on the positive side.

Other discontinuities can also be avoided by overdesigning. A general rule is that the more slots in the rotor the smaller will be the effect of the harmonics. The greater the number of slots the higher will be the torque. This means that excess copper has to be used, and the cost increased.

All these uncertainties point to the need for an accurate, low cost, rapid means of measuring the exact torque speed characteristics of the motor. Once Bill Tyler began to think about the problem, the solution seemed obvious. "Have the motor drive a tachometer and differentiate the signal." Since the tachometer output was proportional to the speed, the derivative of the signal would be proportional to the acceleration. If the acceleration and speed signals are fed into the vertical and horizontal inputs of the oscilloscope, as the motor is accelerated from zero to full speed, the oscilloscope will display a Torque-Speed curve. The calibration should be no problem. The synchronous speed of the motor is known accurately, and the known values of the locked rotor torque can be used to calibrate the torque scale. Alternatively, the torque could be obtained from the relation Torque = I_{α}, where I is the inertia of the rotor and shaft, and α is the angular acceleration. The scope trace would give α and the inertia of the rotor and shaft can be measured.

The solution was obvious, but as far as Tyler knew, the instrument had never been built, probably because accurate differentiation is difficult to obtain. The instrument could require considerable development. Tyler had to decide if the research was worth it.

Was the instrument a luxury or a necessity? After all, the company had been able to get along without it quite nicely for years. Tyler made a rough estimate indicating that in one

year the instrument could save the company from 75 to 100 thousand dollars.

These savings would come from reduced overdesign. Accurate T-N curves of existing designs would give the designers better information. Designers would no longer need to overdesign for safety's sake. Overdesigns usually involve excess copper and copper is expensive. In a $50,000 motor the cost of the excess copper could be as much as $1,000.

Such an instrument would also be useful for new research which Tyler was anxious to undertake. Tyler is constantly comparing his motors with those of the competition. In the large 1200 - 1400 Horsepower motors, Tamper uses 15% less active iron in the laminations than the competition, a substantial saving. To do this, Tamper uses 100% more copper. However, with copper a small portion of the overall weight and a net saving is realized. Tamper's design has 96 stator slots. Some competitors successfully use 48 or 72 slots and group their copper together in a larger coil. The result is a savings in insulation and installation labor. But the smaller number of slots requires a very wide coil, which isn't desirable. Ideally, it is desirable to design for as high and uniform a flux density as possible. The competition actually ends up with a very uneven flux density distribution which should result in unwanted T-N discontinuities. They have been able to overcome this by using magnetic wedges. Tamper has not been able to apply magnetic wedges successfully. Development of this technique is very high on Tyler's list of priorities. To spend time and money on the development of magnetic wedges, Tamper will have to know what the effects of the wedges are. This is where this instrument would become invaluable.

Tyler has hopes that the instrument could become a production test tool. With luck the instrument might be portable with the tachometer hand held against the motor shaft. As a production test instrument it could reveal errors in construction such as a misplaced coil or a cavity in a die cast rotor bar.

At Tamper the work is continual design and redesign. The split between work on established product lines and new designs is approximately even. In Tyler's words, "This is where we carry on any research - in the new design work." Thus the research is tightly controlled by marketing needs.

Tyler decided that the development of the instrument was economically justified. The financing of the project posed no major problems. The departmental operating budget is 1/3 million dollars per year. He also has a little "catch-all

budget" of $2000 for each of his five product lines. He estimated that the cost of development would be about $10,000. He decided to simply distribute the cost over his large motor product line. Normally all projects running over $1000 should be written up as separate proposals with a cost benefit analysis. Such projects would then stand or fall on their own merits. "But not in this case" Tyler decided. "Sometimes the best way to get things done is to break some rules here and there. You can accommodate bureaucracy too far. As long as my department shows a suitable profit there shouldn't be too many questions asked."

Tyler developed his concept to the point at which he thought it was suitable to pass it on to one of his designers. He established the functional black boxes of the instruments and broadly specified the performance parameters.

A survey of the motors that Tamper produced established that usually the torque to inertia ratio was about 8:1 and the rise time varied from .6 to 4 secs. He concluded that one instrument could be made suitable for all motors from 400 RPM to 3600 RPM and 1/4 horsepower to 5000 horsepower. Motors outside this range would have to be tested either by adding additional inertia or by lowering the line voltage of the larger motors.

To define the type of cusp they should be testing for, he used the concept of equivalent frequency. The frequency of the cusp can be defined by its period, frequency being the inverse of the period (Fig. 5). A small calculation established that the discontinuities of interest were at 0-15 cycles per second. Signal frequencies outside this range could be considered as noise and filtered out.

Tyler decided that the instrument should be accurate to within 2.5%. NEMA specifications are worded to require generally not more than 25% accuracy and since this was a measuring instrument, it should be ten times as accurate.

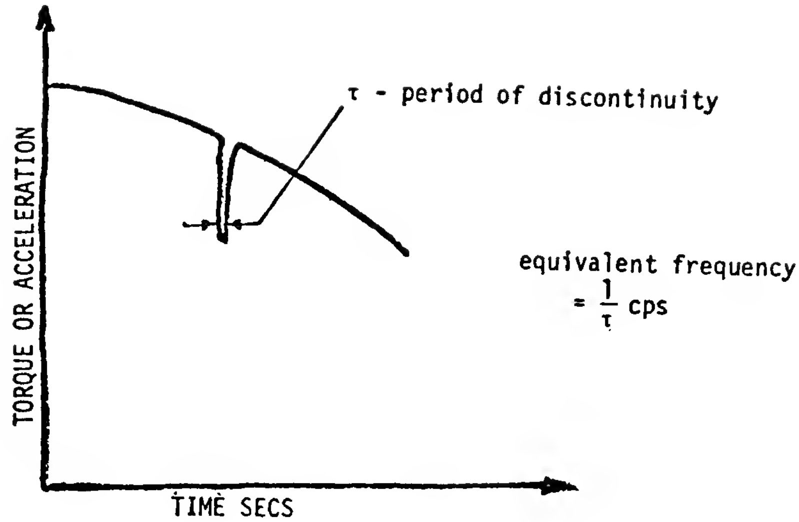


Fig. 5: EQUIVALENT FREQUENCY OF DISCONTINUITY

MEASURING MOTOR TORQUE-SPEED CURVES (B)

Once he had established the performance requirements, Tyler turned the project over to one of his best electronics designers, Odon Bencsics. After Tyler discussed his ideas with Odon, he asked Odon to conduct a feasibility study and to verify the concepts, to design the detail circuitry, to build a prototype and to produce typical torque-speed curves. Once this was accomplished the instrument could be redesigned to make it a production instrument.

Odon Bencsics describes himself as a man of many interests who works at engineering because of circumstances. Bencsics started with Tamper in the late 1950's and at present is a systems designer. Tyler anticipated that Bencsics would develop the prototype instrument without much trouble. He would then have someone else take over the job of productionizing it. Bencsics was too valuable to waste on the final stages.

Bencsics carried out a brief analysis of the requirements. All of Tyler's concepts looked reasonable and he could see no obvious difficulties. He was sure that there were other ways of achieving the same result, but this looked simple enough.

Bencsics started work on the project in May of 1973, while he was still involved in several other projects. The preliminary design was done in about one and a half weeks. This included completing the feasibility study, the initial design of the instrument, and the design of the power supply.

Odon Bencsics describes his development of the circuits as follows:

"Once feasibility had been established I attacked the heart of the problem - the differentiator. I first considered using a simple differentiating operational amplifier circuit (Fig. 6).

After careful consideration it became evident that this circuit would not be satisfactory. Accurate differentiation over the required frequency range of the discontinuities could not be obtained.

Next I considered what could be called a differentiating - integrating circuit. (Fig. 7).

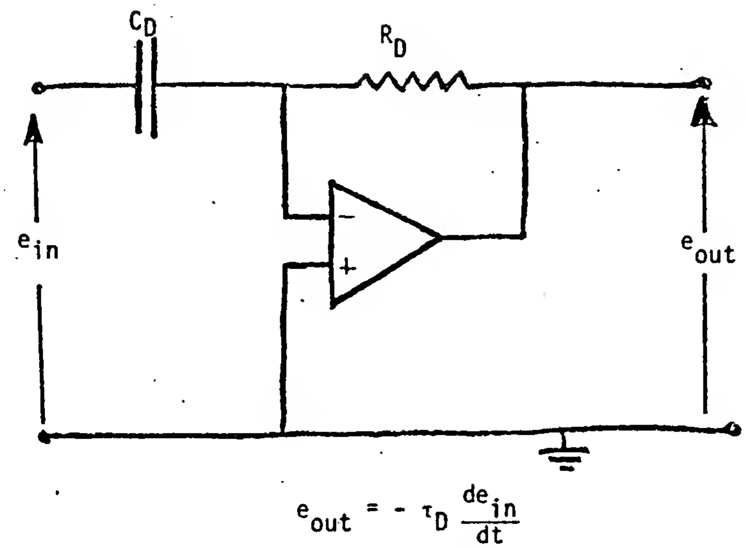


Fig. 6: SIMPLE DIFFERENTIATOR

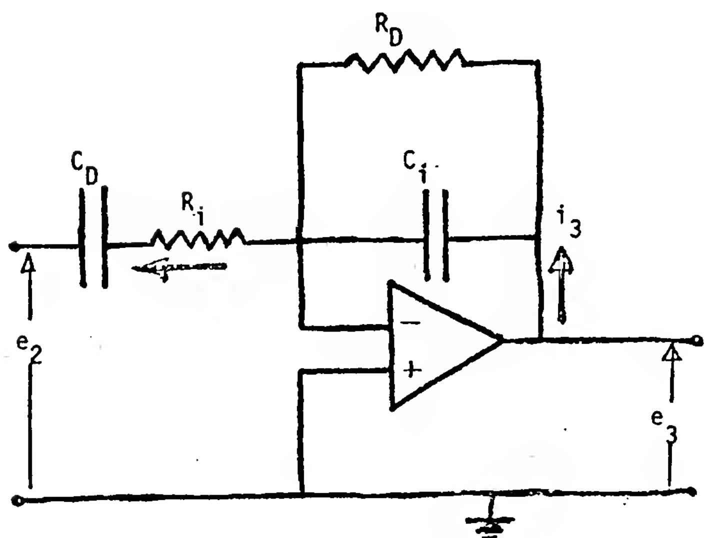


Fig. 7: DIFFERENTIATOR-INTEGRATOR

$$i_2 = \frac{e_2}{R_i + \frac{1}{C_D s}} \qquad i_3 = (\frac{1}{R_D} + C_i s) e_3 \qquad s \text{ - Laplace variable}$$

also $i_2 = i_3$

After a lot of algebraic manipulation

$$e_3 = \frac{-R_D C_D s}{(1+R_D C_i s)(1+R_i C_D s)} e_2$$

now let $\omega_c = \frac{1}{\tau_c}$, $\tau_c = R_i C_D = C_i R_D$

$$\tau_D = R_D C_D$$

and $e_3 = -\tau_D \frac{de_2}{dt} \frac{1}{(1+\tau_c s)^2}$

Circuit operates as follows:

for $\omega = \omega_c$ - band pass filter

$\omega << \omega_c$ - differentiator

$\omega >> \omega_c$ - integrator

It is convenient to expand this equation as follows

$\mu = \frac{\omega}{\omega_c}$ Note: ω - is the equivalent frequency of the signal to be differentiated in rads/sec.

$$j\mu = \frac{j\omega}{\omega_c} \qquad \tau_c s = \frac{j\omega}{\omega_c} = j\mu$$

$$\therefore \frac{1}{(1+\tau_c s)^2} = \frac{1}{(1+j\mu)^2}$$

Rationalizing the denominator gives

$$\frac{1}{\sqrt{(1-\mu)^2 + (2\mu)^2}} \angle \tan^{-1} \frac{2\mu}{(1-\mu^2)}$$

Magnitude and Phase Errors

the entire differentiation equation may now be rewritten as:

$$e_{out} = \underbrace{\left[- \tau_D \frac{de_{in}}{dt} \right]}_{differentiation} \underbrace{\left[((1-\mu^2)+(2\mu)^2)^{-1/2} \right]}_{error\ term} \underbrace{\left[\frac{\tan^{-1} 2\mu}{1-\mu^2} \right]}_{time\ lag}$$

I felt this was a circuit capable of accurate differentiation. The accuracy of the differentiation $- \tau_D \frac{de_{in}}{dt}$ *was dependent on the error term.* $\frac{1}{\sqrt{(1-\mu)^2 + (2\mu)^2}}$

The range over which accurate differentiation was required was 10 to 15 Hz. With ω *equal to 0 - 15 Hz in radians,* ω_c *dependent on circuit parameters could be selected so that* $\mu = \frac{\omega}{\omega_c} \ll 0.1$. *The entire error term would then approach unity and accurate differentiation would be achieved over the required frequency range.*

The problem was in differentiating the discontinuities. The basic T-N curve was no problem, it has a long period which corresponds to a low frequency, resulting in accurate differentiation. In selecting the circuit parameters, I tried to achieve 100% accuracy in differentiating a signal of 5 Hz. For this $\omega_c = 321.09$ *rads.per sec.*

With this I established the values for the circuit elements. For 5 Hz, the phase lag of the differentiator would be 11.42°. *The time lag of one complete period is equivalent to a phase lag of* 360°, *thus the differentiator will have a time lag of 6.2 msec. I also established that for the entire frequency range of 0-11.5 Hz, the time lag remains at 6.2 msec.*

I then performed a complete error analysis. There are two possible sources of error.

One is due to the tolerances of the components used in τ_D circuit. This error could be held to ± 1.45% by using precision components, 0.1% resistors and 1% capacitors.

The second source of error was the error term.

$$\frac{1}{\sqrt{\left(1 - \frac{\omega}{\omega_c}\right)^2 + \left(\frac{2\omega}{\omega_c}\right)^2}}$$

However, the τ_c circuit, like the τ_D circuit could have an error of 1.5% due to components tolerances. Therefore τ_D would have a value equal to ± 3.1148×10^{-3} ± 1.5% from which maximum and minimum error terms can be computed. The error analysis was carried out on a computer (Exhibit #1) . At 5 Hz the net error was + 0.47 to - 2.37%. This is a ± 1.9% error and therefore the effective accuracy is .95%. This is called normalizing the error.

Once the design of the differentiator was completed I considered the other components necessary to support the differentiator. The velocity signal required a lag circuit for if the velocity signal were fed directly to the oscilloscope it will be ahead of the acceleration signal due to the phase lag in the differentiator. The tachometer output also requires an attenuator to normalize the wide range of voltages generated at the test speeds which varied from 400 rpm to 3600 rpm. The input into the differentiator should not exceed 15 volts to avoid saturation of the operational amplifier. The resultant system is shown in Fig. 8.

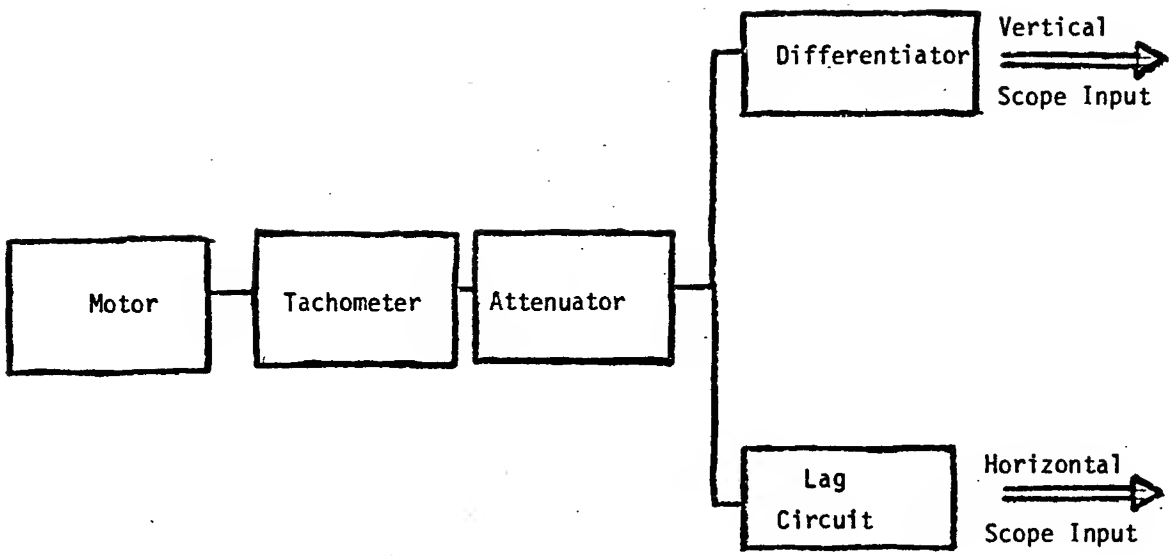


Fig. 8: INSTRUMENT BLOCK DIAGRAM

The lag circuit was established by noting that in the Differentiator-Integrator analysis the term $\frac{1}{(1+\tau_c s)^2}$, *which defines the lag of the differentiated signal, is 6.2 msec. over the entire frequency range of 0 - 15 Hz. The ideal lag circuit for the velocity signal should also have a transfer function of* $\frac{1}{(1+\tau_L s)^2}$ *where* $\tau_L = \tau_c$. *Such a circuit was selected (Fig. 9).*

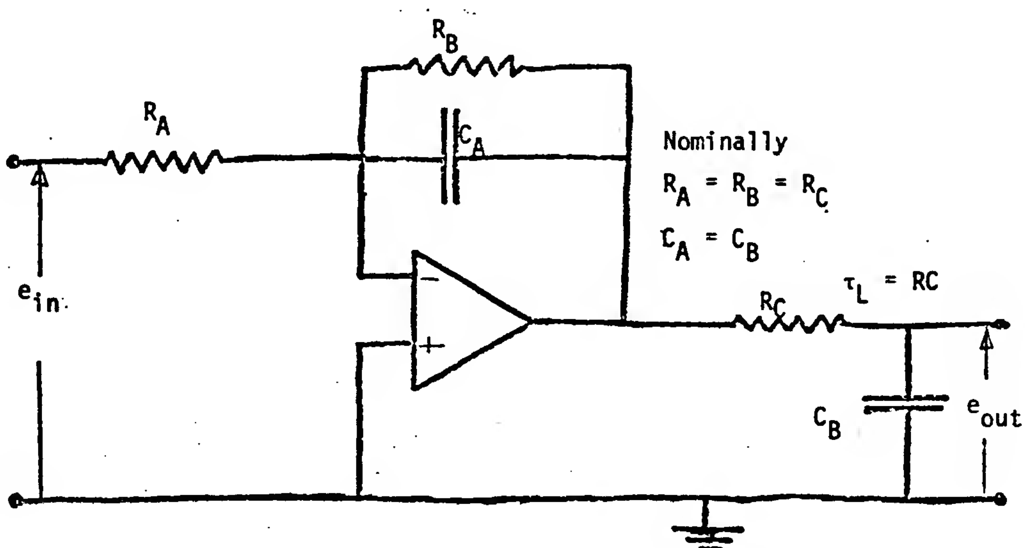


Fig. 9: LAG CIRCUIT

Knowing τ_c, the components to produce τ_L can be easily determined. As with the error term, the gain of the lag circuit will be close to one over the entire frequency range. It can also be shown that the phase lag of this circuit will equal the phase lag of the differentiator to within 4%. To perform the error analysis it must be remembered that the lag circuit has a positive and a negative error because τ_L can have an error of ± 2.5% due to the tolerances of the circuit components. Unlike the differentiator there is also an error associated with the dc gain of the circuit. The dc gain is simply $\frac{R_A}{R_B}$ which, due to choice of components, should equal one, but the associated error is two times the tolerance of each resistor.

The attenuator design was dependent on the tachometer used, in this case a Standco BB-2-40 (Exhibit #2). For a range of 400 RPM - 3600 RPM, the tachometer output voltage would vary from 16 volts dc to 144 volts dc. To prevent saturation, the attenuator had to normalize the maximum output to less than 15 volts regardless of the RPM. The attenuator circuit (Fig. 10) consisted of a voltage divider and an operational amplifier. The op-amp ensured a low input impedance to the succeeding differentiating circuit.

The constant output of the attenuator e_x was set to protect the circuit from a fast rising signal which could drive the op-amp into saturation. If the input is a 1 volts zero-peak sine wave, with ω the equivalent frequency of the input, it can be shown that the maximum rate of change of the input signal is ω (Fig. 11).

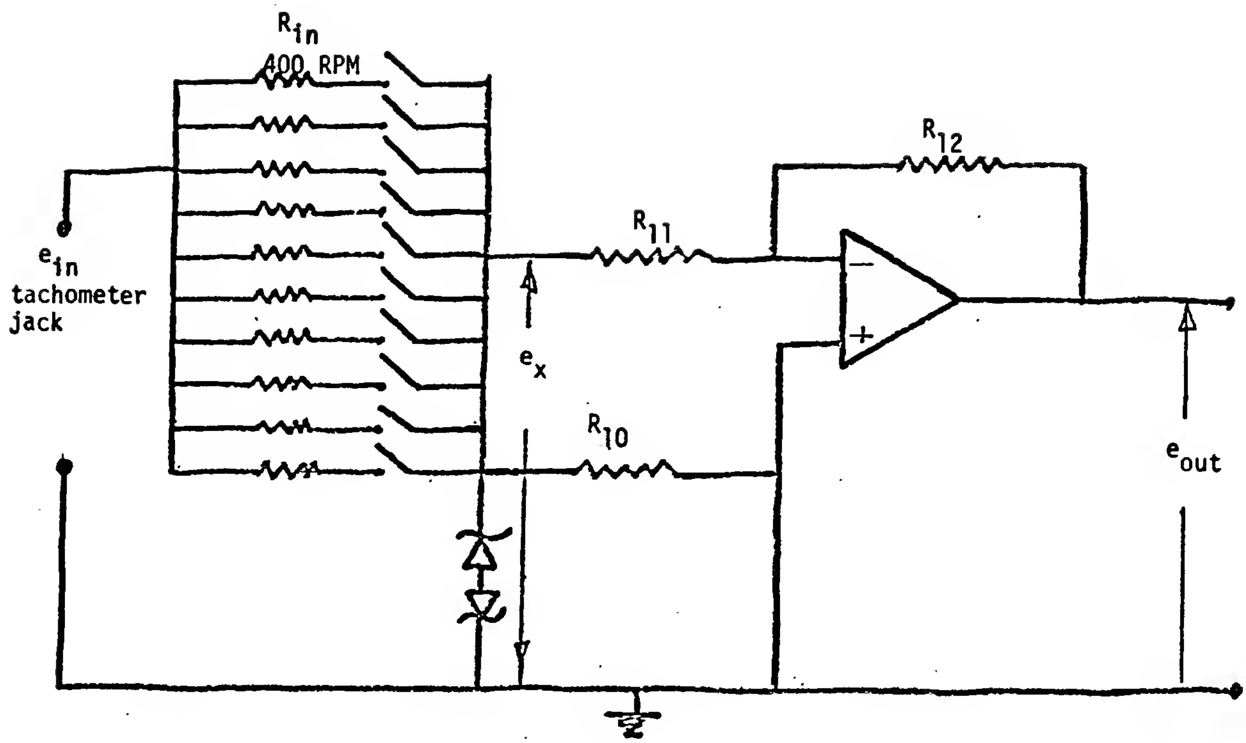


Fig. 10: ATTENUATOR

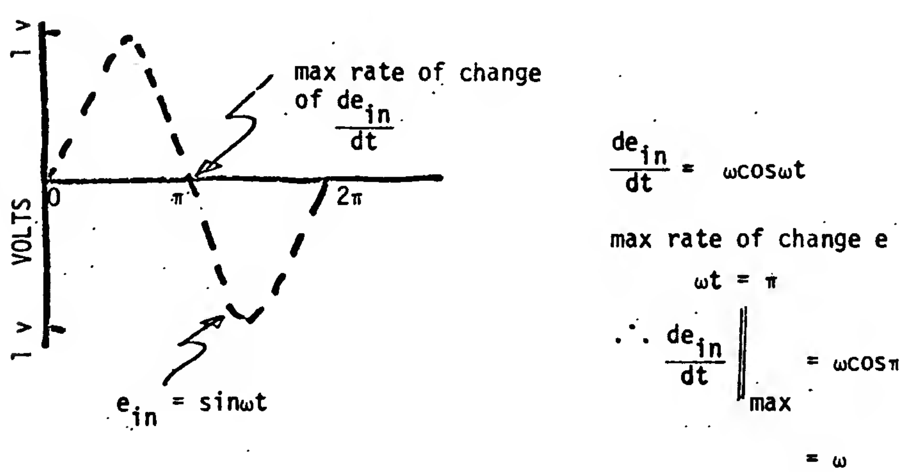


Fig. 11: DERIVATIVE OF INPUT SIGNAL

Designing the circuit for an input frequency of 5 Hz, the maximum allowable rate of change of the input signal which is equal to ω would be 32.1 volts/sec. Any input with faster rise characteristics would saturate the op amps, therefore I selected e_x for an average rate of acceleration. The shortest rise time was 300 msec.; therefore the average acceleration was equivalent to $e_x/0.3$.

Surveying previous motor torque speed curves I found that the largest ratio between maximum acceleration and average acceleration was 2.1.

$$\therefore \left| \frac{de_{in}}{dt} \right|_{max} = 32.1 \text{ volts/sec} = 2.1 \left(\frac{e_x}{.3}\right)$$

$$\therefore e_x = 4.58 \text{ volts}$$

The resistors R_{in} were then chosen so that the voltage divider would give an input voltage of 4.58 volts.

I considered using an automatic attenuator which would select the proper resistor R_{in}. This was rejected because the circuit would introduce fast switching transients which could force the op-amps to saturate, besides it was a complex digital circuit and there wasn't enough room on the circuit boards.

(TRACER : DIFFERENTIATOR)

```
/display tdiff
*IN PROGRESS
/JOB
/FTC NAME=TDIFF
           TD=0.3162
           TC=0.0031148
           PI=3.141592
           OMC=1./TC
           DO 20 I=1,15
           U=I
           U=0.01*U
           OM=U*OMC
           FREQU=OM/(2.*PI)
C    ERMAG = MAGN. ERROR FACTOR
C    ERMAGP = MAGN. ERROR, PC.
C    ERPH = PHASE ERROR, RADIAN
C    ERPHD = PH. ERROR, DEG.
C    TL = TIME LAG, MSEC.
           ERMAG=1./SQRT((1.-U**2)**2+(2.*U)**2)
           ERMAGP=-(1.-ERMAG)*100.
           E3=OM*TD*ERMAG
           TL=-1000.*(TC/U)*ATAN(2.*U/(1.-U**2))
           ERPH=-ATAN(2.*U/(1.-U**2))
           ERPHD=180.*ERPH/PI
           WRITE(6,10)OM,FREQU,E3,ERMAGP,ERPHD,TL
10         FORMAT(6E14.5)
20         CONTINUE
           END
*END

*GO
```

EXHIBIT 1

Table 1. MODEL B GENERATOR RATINGS

Type	Mounting	Nominal Voltage Rating at 1000 RPM	Maximum Permissable Speed RPM	Maximum Current	Permissable Load at 1000 RPM*	Armature Resistance At 70°F	Actual Voltage Output At 1000 RPM With No Load Connected	Actual Voltage Output At 1000 RPM With 4 Watt Load Connected
BB-2-100	Base Mounted	100V D.C.	5400	40 MA	4 Watts	205 Ohms	110V D.C.	100V D.C.
BF-1-100	Flange Mounted	100V D.C.	5400	40 MA	4 Watts	205 Ohms	110V D.C.	100V D.C.
BB-2-40	Base Mounted	40V D.C.	9000	100 MA	4 Watts	30 Ohms	44V D.C.	40V D.C.
BF-1-40	Flange Mounted	40V D.C.	9000	100 MA	4 Watts	30 Ohms	44V D.C.	40V D.C.

**Maximum Load is 12 Watts at 3000 RPM. If generators are driven at higher speeds (up to maximum permissable speeds) the external load resistance must be sufficient so that the maximum load is not exceeded.*

SPECIFICATIONS

Type BB-2-100 - Base Mounted Type BF-1-100 - Flange Mounted		Type BB-2-40 - Base Mounted Type BF-1-40 - Flange Mounted	
Voltage Output	100V DC per 1000 RPM	Voltage Output	40V DC per 1000 RPM
Maximum Permissible Speed Range	5400 RPM	Maximum Permissible Speed Range	9000 RPM
Maximum Load Rating	40 milliamperes DC	Maximum Load Rating	100 milliamperes DC
Lead Connections	Under terminal cover box	Lead Connections	Under terminal cover box
Bearings	Ball Bearings	Bearings	Ball Bearings
Enclosure	Totally enclosed	Enclosure	Totally enclosed
Internal Resistance	205 ohms	Internal Resistance	30 ohms
Temperature Coefficient	0.03% per degree C	Temperature Coefficient	0.03% per degree C
Ripple	Less than 0.5%	Ripple	Less than 0.5%
Static or Breakaway Torque	1.95 oz. in.	Static or Breakaway Torque	1.95 oz. in.
Reversing Error	Less than 0.5%	Reversing Error	Less than 0.5%
Field	Alnico	Field	Alnico
Armature	15 slots, 45 bars	Armature	15 slots, 45 bars
Number of Poles	2	Number of Poles	2
Brushes	2	Brushes	2
Mounting	BB-2-100 - base BF-1-100 - flange.	Mounting	BB-2-40 - base BF-1-40 - flange.
Shaft Extension	1.18"	Shaft Extension	1.18"
Shaft Diameter	.276" flange, .433 base	Shaft Diameter	.276" flange, .433 base
Approx. Overall Length	6.88"	Approx. Overall Length	6.88"
Net Weight	5 lbs. 2 oz.	Net Weight	5 lbs. 2 oz.

HERMAN H. STICHT CO., INC. • 27 PARK PLACE • NEW YORK, N.Y. 10007

EXHIBIT 2

MEASURING MOTOR TORQUE-SPEED CURVES (C)

Within 1-1/2 weeks Bencsics had completed a suitable design and the instrument was ready for construction. Unfortunately, because of other commitments, a technician couldn't be made available. He therefore undertook to build the instrument himself.

His principal concern in building such an instrument was the accuracy of the components. He started by choosing his operational amplifiers. From the specification sheet (Exhibit 3), he concluded that because of the extremely low offset voltage, with offset and bias currents of only few pico-amps, and almost non-existent drift, for his purposes he could consider them as ideal units. The remaining components were high precision components, 0.1% and 1.0% capacitors. Whenever series or parallel combinations of the components were used, he would set their values by trimming. For capacitors he used the following circuit (Fig. 12).

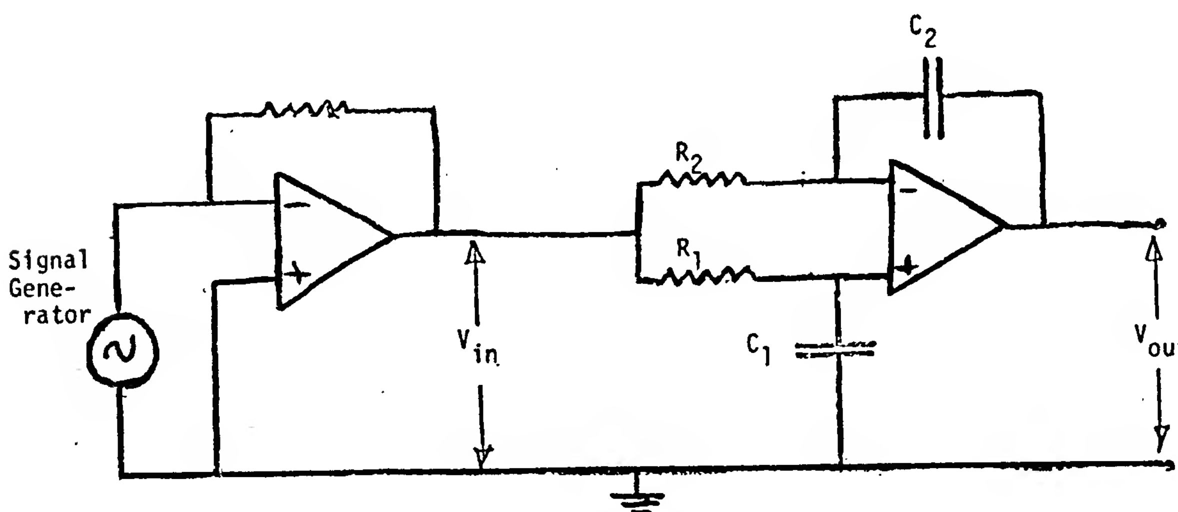


Fig. 12: TRIMMING CIRCUIT

The first op-amp was used to provide the circuit with a low input impedance. If the precise values of R_1, R_2, and C_1 are known and a null is obtained at V_{out} with C_2, then the exact value of C_2 may be determined. After some manipulation it

may be shown that $ZC_2R_1 = ZC_1R_2$ where ZC is the impedance of a capacitor. The exact values of resistors were determined with a wheatstone bridge.

The greatest problem in construction was the limited supply of precision components. To establish his time constants and circuit parameters, Odon was restricted to those high precision components that were available in the lab. There were 25 0.1% resistors and 12 1% capacitors. He didn't want to order special components to suit his specifications because they were not available locally and they cost about thirty times more than components of standard precision. When he built the circuits the first time he found that towards the end he didn't have the correct components left to finish his circuit because of the combination of components previously used. Keeping in mind what he had learned from his first attempt he redid the design using different combinations of components to build his circuits.

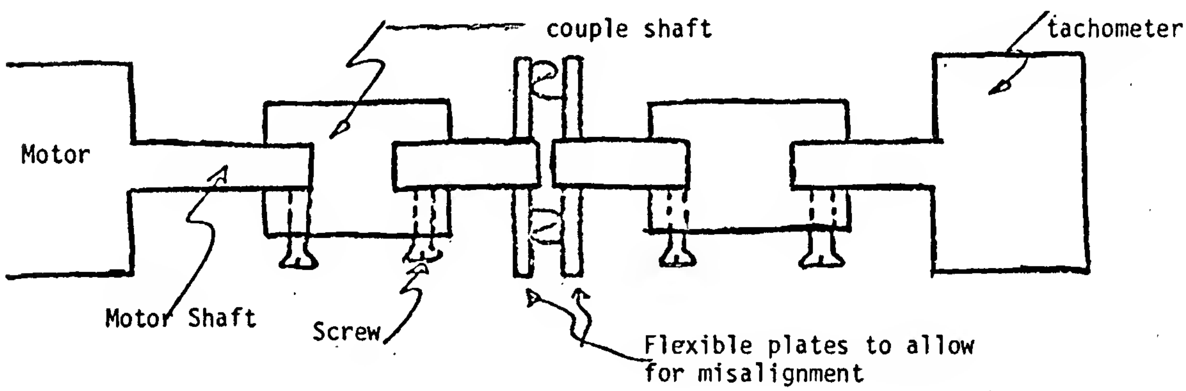


Fig. 13: TACHOMETER COUPLING

When the instrument was tested, the T-N trace on the oscilloscope revealed a great deal of noise which exceeded tachometer specification by a factor 10. Odon was certain that the problem was one of alignment, (Fig. 13), that the instrument could be improved if additional filters were set between the acceleration and velocity outputs and the scope.

Another problem also emerged in testing. Before recording a test trace, Odon made several runs which he used to adjust the scope controls so that the trace would cover the entire face of the oscilloscope. He would first adjust the zero point at the left of the screen, then run the motor at full speed and attempt to locate the signal at the far right of the screen by adjusting the horizontal gain. In doing this he constantly lost his initial zero position and it took many attempts to get a suitable trace. This could be simplified if if the lag circuit had a built-in adjustable gain.

With these changes in mind, Odon went back to his desk to redesign the circuit. The redesign of the filters and lag circuit took approximately one week to complete. The new lag circuit incorporating the adjustable gain is shown in Fig. 14.

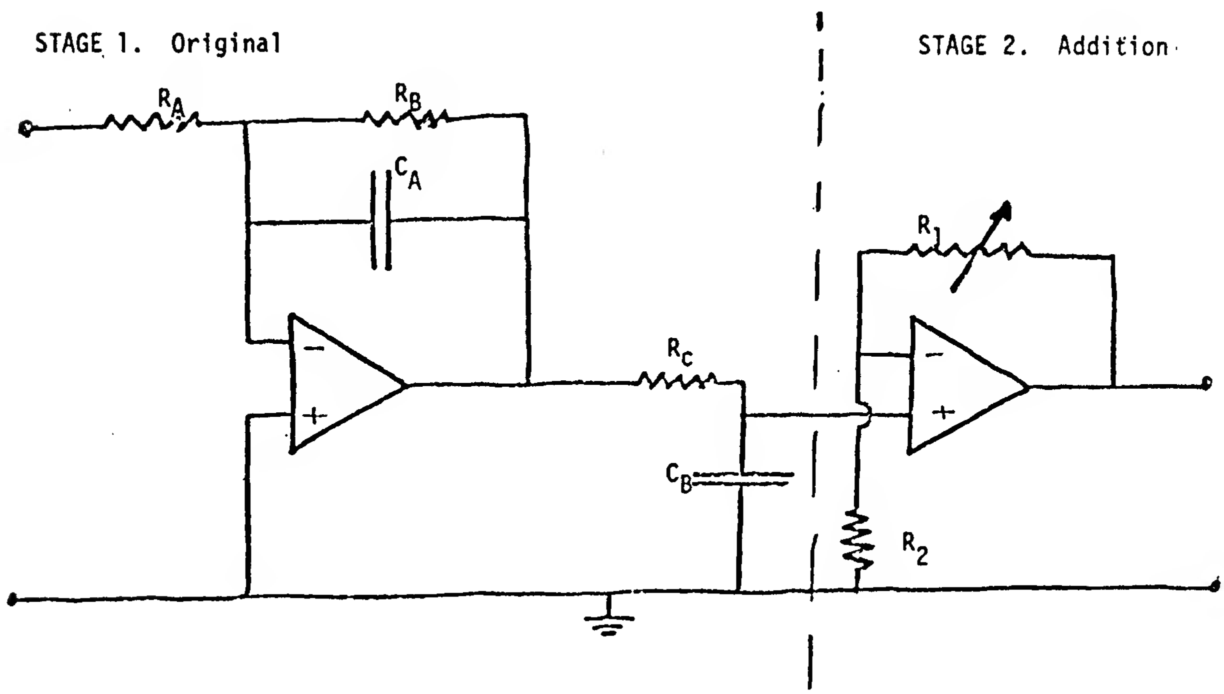
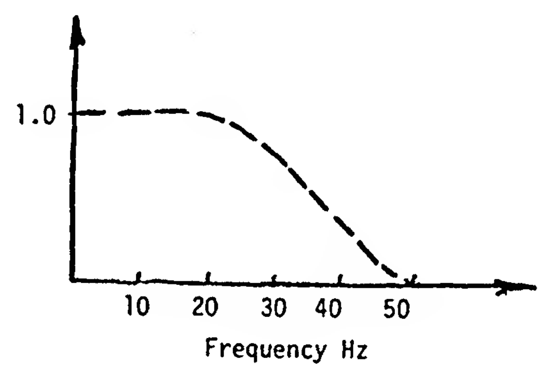


Fig. 14: MODIFIED LAG CIRCUIT

By the addition of a second stage the time lag of the transfer function was not altered but the gain was changed to $\frac{R_1 + R_2}{R_2}$.

It should be noted that stage two is used as a non-inverting amplifier and that the gain can be adjusted from 1 to $\frac{R_1 + R_2}{R_2}$.

Odon expected that his design would eliminate any noise because it integrated the higher frequencies and the integral of a short cusp would be very close to zero. But to achieve accurate differentiation of a 5Hz signal ω_c had to be set at 55 Hz or 321.09 rads/sec. The tachometer specifications however stated that inherent noise would be in the 50 Hz range and for this the differentiator acted as a bandpass filter. To solve this, Odon decided on a filter to block out the tachometer noise. He knew that no relevant cusps on the T-N curve would be above a frequency equivalent to 15 cps. From this he determined the desired bandpass.



BANDPASS OF FILTER

This filter need only have been added to the acceleration signal. To compensate for phase lag, however, an additional identical filter was added to the velocity signal. Time lag equalization is thus within 2 msec. To accomplish this, he used a Butterworth filter (Fig. 15).

The addition of these low pass filters, however, involves a compromise. Because of the tolerances on the components, the gain of the filter could never be exactly equal to one, resulting in an inherent error of 1%. For the specific application, a decision has to be made as to whether to have an accurate noisy output or a noise free curve with the subsequent reduction in accuracy. The net errors of the instrument with and without the low pass filters are tabulated in Exhibit 4.

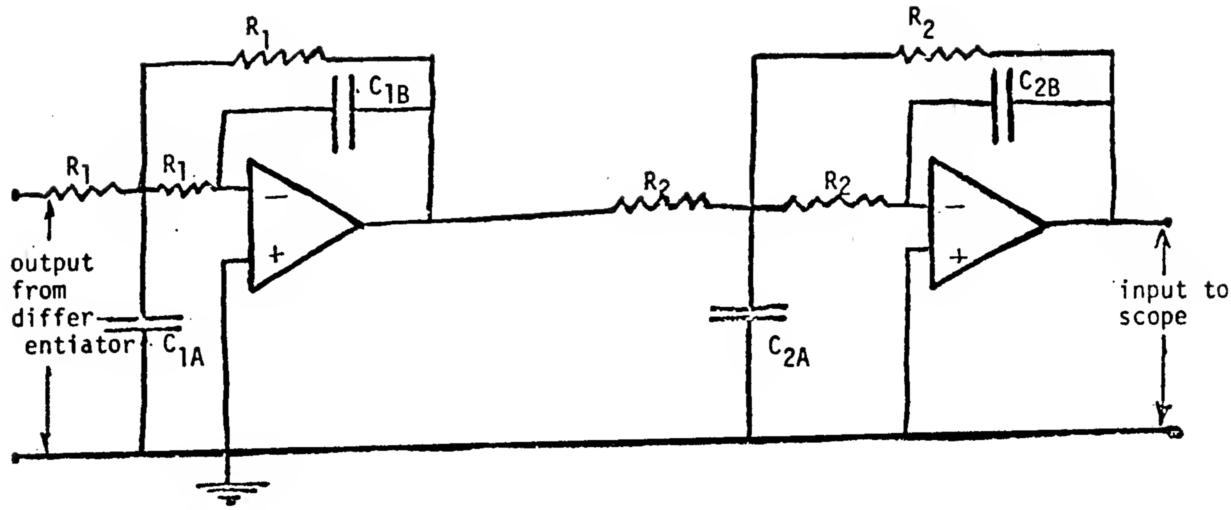


Fig. 15: LOW PASS FILTER

In constructing these additional circuits the lack of precision components became acute. Once again he ran short of exact components. At this point he considered writing a computer program which would help him choose components. This, however, would be complex and he decided to start again.

He described his method as follows "It was a mental process of anticipation. At each stage, you try to foresee how to use your components most intelligently. At each iteration you try to anticipate problems on the basis of experience." Odon was lucky. He produced a successful instrument on the second try.

Odon found this job of trying to match the components, testing and trimming components, building the circuit and housing for the instrument, slow, boring and tedious. He estimated that of the two months which he spent on the project, over half the time was spent on this part of the job.

When he first tested the instrument with the added features he still obtained noisy traces. Then by experimenting with the alignment of the tachometer he was able to obtain reasonable results. He was therefore certain that the remaining problem was simply one of alignment. To overcome this he recommended that if a rubber tipped tachometer is used its support should be made rigid and its location exactly controlled. The tip should be centered on the shaft and constantly checked for overheating and wear.

The kind of results that can be obtained are shown in Fig. 16. The acceleration versus time output is used to measure the period of the cusps and thereby determine the equivalent frequency. Differentiating between cusps is no problem since they occur sequentially. The trace is produced with the motor accelerating and starting from reverse rotation. This avoids any switching transients affecting the T-N curve.

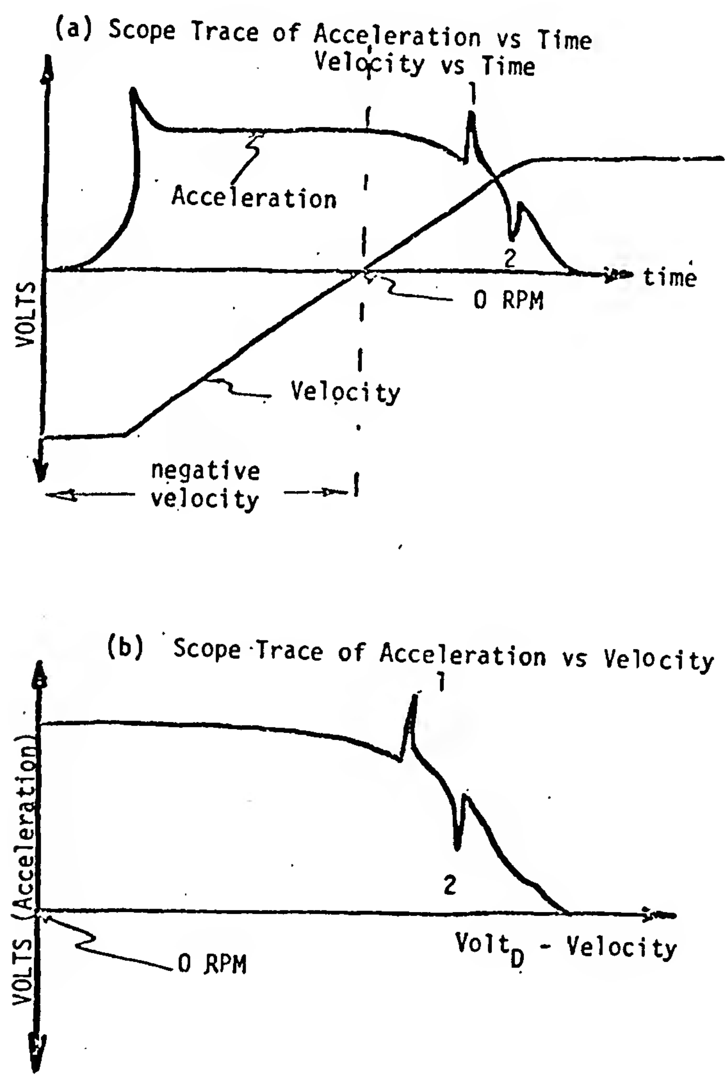


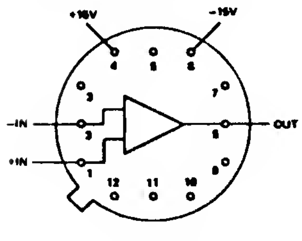
Fig. 16: SCOPE TRACES

Exhibit 5 is a sketch of the finished instrument. It is approximately 9 inches by 9 inches. Three circuit boards are used with the remaining three left for planned future additional functions. The circuit diagram for board No. 2, the low pass filters, is shown in Exhibit 6. The 15 Volt D.C. power supply circuit is shown in Exhibit 7. This makes available 250 milliamps of which only 100 milliamps is currently used.

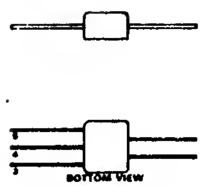
Odon Bencsics described this project as very problem free. It took two months to complete because of many interruptions from other projects and summer holidays. The only real problem was juggling for the appropriate precise component values. He estimates the total cost of components was about $250. Odon finds it very strange that such an instrument hadn't been developed before. As to patents, he doesn't feel that any of this work is suitable for patent. "After all, the ideas are known and the components are known, so what is there left to patent?"

FET-INPUT GENERAL PURPOSE OP AMPS
AD501, ADM501, ADP501

PIN CONFIGURATIONS
Bottom View

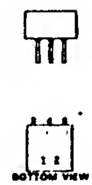


ADM501



AD501

PIN 1: INVERTING INPUT
PIN 2: NON-INVERTING INPUT
PIN 3: +15VDC
PIN 4: −15VDC
PIN 5: OUTPUT



ADP501

GENERAL DESCRIPTION

The Analog Devices Model AD501 is a microcircuit FET input operational amplifier that is supplied in the industry-standard axial-lead and plug-in molded packages, and in the hermetically sealed TO-8 type of package. The AD501 features offset voltages of less than 1mV, offset voltage drifts below 25μV/°C and bias currents of less than 5pA. The circuits are manufactured with strictly controlled hybrid assembly techniques, which have proven their high reliability and fault-free performance through three years of system usage. The AD501 is supplied in the end-lead mini-package; the ADP501 in the bottom-lead mini-package; and the ADM501 in the TO-8-type package.

ELECTRICAL CHARACTERISTICS (V_S = ±15V, T_A = +25°C,* unless otherwise noted)

Parameter	Conditions	501A P501A M501A	501B P501B M501B	501C P501C M501C	Units
Initial Input Offset Voltage (max)	R_S < 100kΩ	2.0	1.0	1.0	mV
Average Temp Coef of Input Offset Voltage (max)	T_A = −25°C to +85°C	75	25	25	μV/°C
Initial Input Bias Current (max)**		25 (10pA M501)	10	5.0	pA
Average Temp Coef of Input Bias Current (typ)**	T_A = 25°C	2.5 (1pA/°C M501)	1.0	0.5	pA/°C

ALL DEVICES

Parameter	Conditions	MIN	TYP	MAX	Units
Large Signal Voltage Gain	R_L > 2kΩ, V_O = ±10V	25,000	100,000		V/V
Input Resistance	Differential		10^{11}		Ω
	Common Mode		10^{11}		Ω
Input Capacitance			4		pF
Input Noise Voltage (rms)	5Hz to 50kHz		6		μV
Input Voltage Range		±10	±12		V
Common Mode Rejection	V_{IN} = ±5V		80		dB
Supply Voltage Rejection			50		μV/%
Output Voltage Swing	R_L > 10kΩ	±12	±14		V
	R_L > 2kΩ	±10	±13		V
Output Short Circuit Current			25		mA
Supply Current				9	mA
Slew Rate		3	5		V/μs
Unity Gain Bandwidth			4		MHz
Full Power Response	R_L > 2kΩ, V_O > 10V	70			kHz
Price (1–9)	501	39.00	45.50	52.00	$
	P501	39.00	45.50	52.00	$
	M501	45.50	52.00	58.50	$

*Typical Junction Temperature (T_J) is 10°C above Ambient Temperature (T_A) after 15 minutes warm-up at V_S = ±15V.
*Doubles every 10°C.

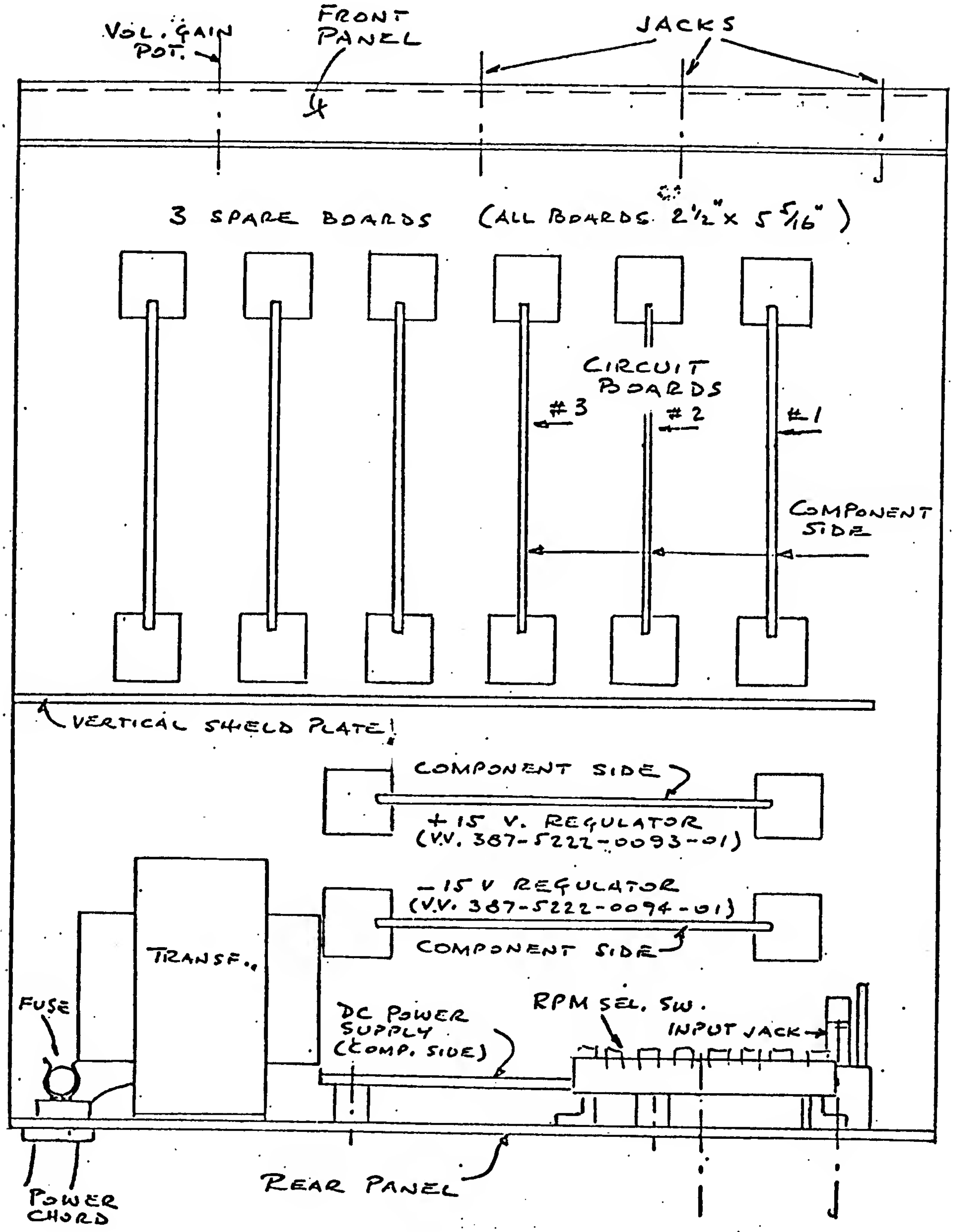
RANGE OF MAX. (MAGNITUDE) ERROR IN ACCELERATION OUTPUTS

FREQU. Hz	Differentiator Error ACCEL. 1: e3 vs. (de2/dt).Kd %		Filter Error * e5 vs. e3 %		* ACCEL. 2: e5 vs. (de2/dt).Kd %	
1	+ 1.41	- 1.49	+ 0.0	- 0.0	+ 1.41	- 1.49
2	+ 1.29	- 1.60	+ 0.0	- 0.0	+ 1.29	- 1.60
3	+ 1.09	- 1.78	+ 0.1	- 0.1	+ 1.19	- 1.88
4	+ 0.82	- 2.04	+ 0.2	- 0.2	+ 1.02	- 2.24
5	+ 0.47	- 2.37	+ 0.3	- 0.3	+ 0.77	- 2.67
6	+ 0.05	- 2.77	+ 0.4	- 0.4	+ 0.45	- 3.17
7	- 0.44	- 3.23	+ 0.5	- 0.5	+ 0.06	- 3.73
8	- 1.01	- 3.77	+ 0.7	- 0.7	- 0.31	- 4.47
9	- 1.64	- 4.37	+ 0.8	- 0.9	- 0.84	- 5.27
10	- 2.34	- 5.03	+ 1.1	- 1.0	- 1.24	- 6.03
11	- 3.10	- 5.75	+ 1.3	- 1.2	- 1.80	- 6.95
12	- 3.92	- 6.53	+ 1.5	- 1.4	- 2.42	- 7.93
13	- 4.80	- 7.36	+ 1.7	- 1.7	- 3.10	- 9.06
14	- 5.73	- 8.24	+ 1.9	- 1.9	- 3.83	-10.14
15	- 6.70	- 9.16	+ 2.2	- 2.2	- 4.50	-11.36
16	- 7.72	-10.14	+ 2.3	- 2.5	- 5.42	-12.64
17	- 8.78	-11.15	+ 2.5	- 2.9	- 6.28	-14.05
18	- 9.88	-12.19	+ 2.6	- 3.3	- 7.28	-15.49
19	-11.02	-13.27	+ 2.5	- 3.8	- 8.52	-17.07
20	-12.18	-14.35	+ 2.4	- 4.3	- 9.78	-18.65
25	-18.33	-20.30	+ 0.0	- 9.9	-18.33	-30.20
30	-24.75	-26.51	+ 0.0	-25.1	-24.75	-51.61

* ADDITIONAL DC LEVEL ERROR = -0.2%

EXHIBIT 4

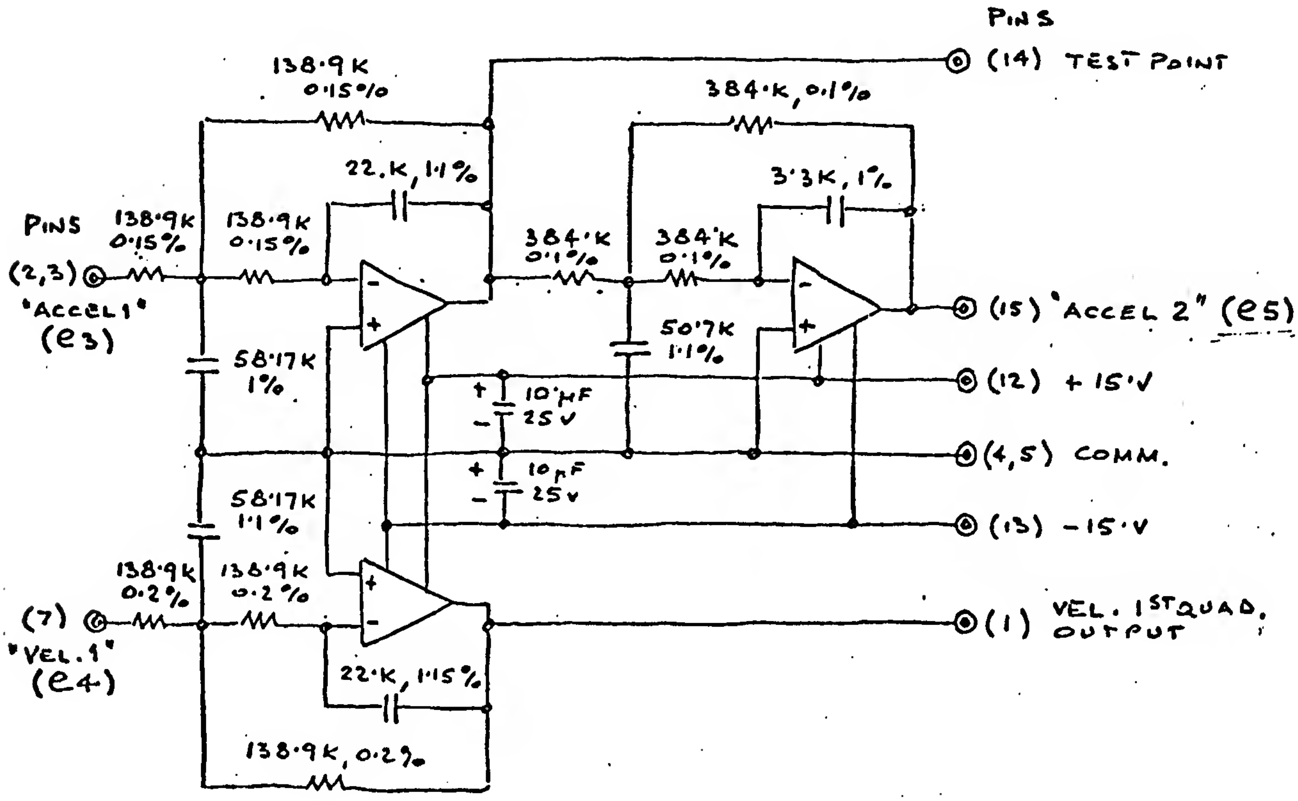
LOCATION OF COMPONENTS (TOP VIEW)



(APPROXIMATELY TO SCALE)

EXHIBIT 5

CIRCUIT BOARD #2 (ACCEL. FILTER, 1ST & 2ND QUADRATIC
VEL. FILTER, 1ST QUADRATIC)



PIN Nº S : 1 TO 15, FROM LEFT TO RIGHT
AS SEEN ON COMPONENT SIDE

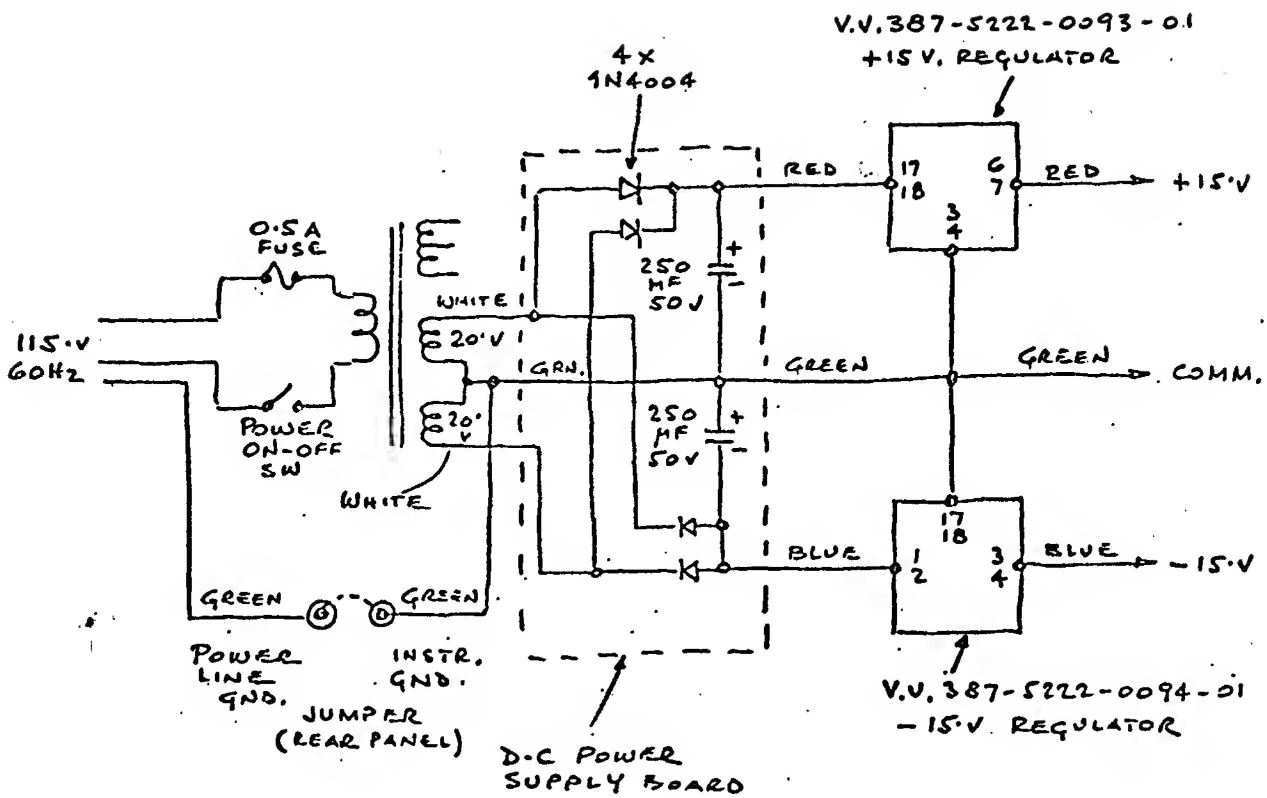
EXTERNAL CONNECTIONS:

PIN 1 ——— TO BOARD #3, PIN 14,
2,3 ——— TO BOARD #1, PIN 14, AND
"ACCEL 1" JACK (FRONT PANEL)
7 ——— TO BOARD #1, PIN 1, AND
"VEL. 1" JACK (FRONT PANEL), AND
VEL. GAIN POT. (FRONT PANEL)
15 ——— TO "ACCEL. 2" JACK (FRONT PANEL)

AMPLIFIERS: ANALOG DEVICES # 501 C
ALL RES. : ¼ W

EXHIBIT 6

POWER SUPPLY CIRCUIT



MAX LOAD ON REGULATORS : 250. mA

MEASURING MOTOR TORQUE-SPEED CURVES (D)

Tyler summed up the work by saying "The accuracy of the instrument was simply incredible." Tyler was anxious to get the torque speed measuring instrument onto the motor production line, but was delayed by a manpower shortage. He was finally able to assign a man to the task of productionizing the instrument. The task was to detect any difficulties with the instrument, and to develop simple operating procedures. "You can't give a production test man 15 wires to connect; you have to reduce the operation down to one button and one plug." Tyler also wanted the T-N curve to be as noise free as possible so as not to confuse the test men.

The use of the instrument almost immediately became stalled because of two very important problems: the required alignment between motor and tachometer, and the instrument was too accurate.

As more traces of test motors were taken, an unexpected result appeared. An induction motor usually runs at a rated speed of 3% to 4% below the synchronous speed. The test traces showed that when the motor accelerates it overshoots the synchronous speed into the negative torque region. After a period of oscillation, the motor settles down to rated speed (Fig. 17).

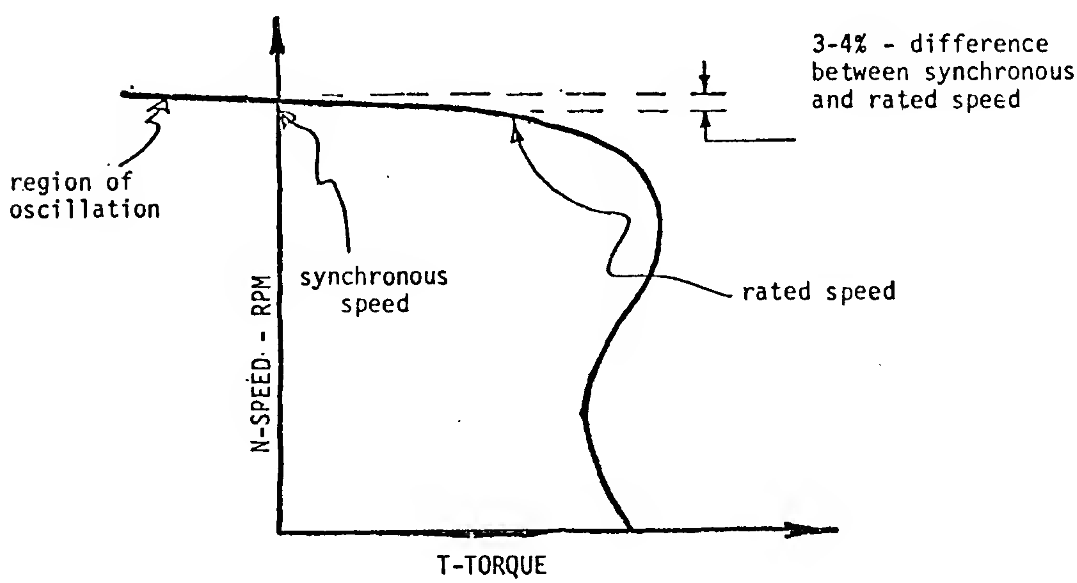


Fig. 17: OSCILLATION AT RATED SPEED

Tyler's first reaction was, "I don't believe it. No one had ever predicted this." For confirmation a check was made using a strobe light. Here too, careful observation showed the motor temporarily shoot past synchronous speed. "It may seem that by worrying about this effect we are starting to split hairs but we will have to do more investigation before we decide to ignore it," was Tyler's comment.

The solution to the alignment problem could involve the overshoot problem. To make the instrument portable, additional filters will have to be added, but these filters could also block out the overshoot effects. It seems that a rigid mount with a mechanical alignment adjustment between motor and tachometer will have to be designed. Although this may no longer be portable, the instrument will still be extremely useful as a production tool.

To serve as a design tool, a third trace will have to be incorporated into the instrument: line voltage vs. time. If there is a discontinuity in that T-N curve, the additon will distinguish if the discontinuity is caused by a drop in line voltage. Line voltage is prone to many irregularities especially at start-up when the motor is drawing 600-700% normal current. The test procedure would be to first test at rated voltage. If an unexplained discontinuity is observed, then another test would be run at a lower voltage to see if the discontinuity was due to saturation. If not, then other reasons would be looked for.

The reasons for the discontinuities could be many: tooth tip saturation, unequal current in rotor bars, poor mathematical design. For design, it is much more important to know the speed at which a discontinuity exists than to know its magnitude.

Up to this point the project has cost $7,000. The finished instrument is expected to cost about $10,000. Tyler admits that there have been questions asked about these expenditures. "But I've been too busy to answer them. The real answer is we're going to get the damn thing working." He expects that the instrument will be on the production line in about three months.

If the instrument proves its value on the production line, the department will then ask the company for funds to develop the instrument further. For example, instead of the present method of photographing the oscilloscope traces, they would like a $12,000 storage oscilloscope with reproduction facilities. Such an instrument would automatically draw the trace on a piece of paper.

Another possible alternative is digital sample and hold units. In this case the acceleration signal would simply be differentiated once more and when the second derivative is zero, the coordinates of the point would be recorded by digital sample and hold units for storage. This could increase the accuracy of measurement. The present instrument is so accurate on most parts of the curve that the principle error is due to parallax in reading the scope. Digital recording of these points would eliminate this.

Tyler remarked, "This approach would fit into our overall test philosophy for the future. Whenever we have to replace an analog meter we do so with a digital unit. Eventually, I can see all our test results being read by remote digital meters. The readings would be automatically wired into our computers where programs will reduce them to meaningful measures such as horsepower for power factor."

The development of this instrument may be characterized as a search for information. The company is always in need of information that is useful and accurate. Tyler admits, "We're not proud. We'll go to any lengths to get information. It is only by having the latest information that we can keep ahead in this continuous rat-race." It's the information which the instrument will produce which will be of value to Tamper in the competitive market and not the instrument itself. Tamper has no intention of producing the instrument for sale because it isn't their type of product.

The instrument will be valuable on another special sort of market -- the information market. Tamper works very closely with some of its competitors. The designers know each other and will often get together to exchange "equal amounts" of information so that both will benefit. It is on such an information market that the instrument takes on a sepcial value.